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Monitoring Current, Voltage and Power in Photovoltaic Systems

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***Abstract* — Accurate photovoltaic system performance monitoring is critical for profitable long-term operation. Irradiance, temperature, power, current and voltage signals contain rapid fluctuations that are not observable by typical monitoring systems. Nevertheless these fluctuations can affect the accuracy of the data that are stored.**

We closely examine electrical signals in one operating PV system recorded at 2000 samples per second. Rapid fluctuations are analyzed, caused by line-frequency harmonics, anti-islanding detection, MPPT and others. The operation of alternate monitoring systems is simulated using a wide range of sampling intervals, archive intervals and filtering options to assess how these factors influence final data accuracy.

***Index Terms* — photovoltaic systems, monitoring, sampling rate, analog filter, digital filter, decimation**

I. INTRODUCTION

The number of PV systems feeding electricity into the grid is growing rapidly. At the same time, awareness is growing of the benefits of carefully monitoring the operation of these systems. This is in part brought on by increases in system sizes, which involve larger investments and larger revenue streams. Keeping close tabs on system operation is one way to mitigate financial risks.

The capabilities of the available monitoring equipment, and also the self-monitoring capabilities of many major components such as inverters, have been continually enhanced to meet this need. The net result is that PV systems are now capable of generating large volumes of operational data, and it can become a challenge to transmit, store and/or process this data, and extract the desired intelligence in a timely and effective manner.

This study has two main components. First, it takes a detailed look at the most important electrical signals that are monitored in PV systems using data collected at 2000 samples per second to find out what measurement challenges each signal holds. It then explores how different ways of processing and sampling these signals can affect the accuracy of the data that are archived in logs and databases. More details are found in a Sandia Technical Report [1].

II. BACKGROUND

Much of what has been written about PV monitoring focuses on the analysis and interpretation of operational data that has been collected. This is not surprising because the value of the monitoring effort lies there. However the prerequisite measurement processes cannot be taken for granted. It is very possible to come to the wrong conclusions about a PV system's status based on inaccurate data.

Accuracy involves much more than a number on a spec sheet. If a data logger can take a single voltage measurement with an accuracy of ±1%, what does that mean for the accuracy of hourly values in the log files? To answer this and similar questions, we need to examine the process by which measurements are converted to log entries. This typically involves taking more than one measurement and calculating an average, but there are many other relevant details.

PV monitoring system operation can be decomposed into a sequence of basic steps. Some monitoring systems may offer a little more or less functionality of course, but we are interested in differences arising in the same core operations. For example, all systems do analog to digital conversion, but they may do so at different rates. Whether this analog to digital conversion takes place at the data logger or inside a smart combiner box is less important.

The complete sequence of steps leading from a signal to a value in a data log or archive is referred to as a "measurement chain". In the following section we describe the steps comprising a measurement chain and identify the key parameters in each step that may vary between different monitoring systems.

A. Physical to Electrical Conversion

Many of the signals in PV monitoring systems are electrical in nature at the source, allowing a voltage or current to be measured directly or via an electrical transducer. Other signals require what would normally be referred to as a "sensor" to convert some other physical quantity to an electrical one. The main sensor types are the irradiance sensors, such as pyranometers and reference cells, and temperature sensors, such as thermocouples and temperature-dependent resistors (RTDs).

B. Analog Processing

Electrical signals, whether they are produced by a sensor or obtained directly from an electrical system, frequently need some processing before they can be digitized. The main types of processing are:

Amplification. A signal that is too large or small requires an amplifier with the appropriate gain. An amplifier providing isolation may also be needed to ensure safe operation.

Line-frequency filtering. Signals are often tainted with line-frequency noise (60 Hz in North America) and harmonics that must be removed.

Low-pass filtering. A signal may contain legitimate but unwanted high-frequency content. To capture high-frequency content a high sampling rate is required. (Theoretically twice the highest frequency, and in practice even higher.) When lower sampling rates are used, the high-frequency content from the original signal reappears in the sampled signal as low frequencies that are impossible to distinguish from the original low-frequency content, an effect called *aliasing*. This can be prevented by filtering out high-frequency content above half of the sampling rate *before* sampling. A low-pass filter used for this purpose is referred to as an anti-aliasing filter.

RMS conversion. For AC current and voltage signals the rapid oscillations may not be of interest, but a simple low-pass filter would only produce an average values of zero. The root-mean-square (RMS) values can be calculated instead to obtain magnitudes that are more meaningful on a larger time scale.

C. Analog to Digital Conversion

The A/D conversion step is the transition from the continuous analog world to the discrete digital world: voltage levels are converted to numbers at regular time intervals. The main parameters of interest here are the magnitude resolution, specified by a number of binary bits, and the time resolution or sampling rate. Analog amplification should ensure that the signal range fully utilizes the available range of discrete digital values, and analog filtering should take into account the sampling rate to prevent aliasing.

There are other useful features, such as the ability to integrate a signal over a specified time interval rather than take a (nearly) instantaneous reading. Integration over the duration of a line frequency cycle (16.7 ms. for 60 Hz) can be used to filter out line frequency noise, for example.

D. Digital Processing

After the analog signal is reduced to a series of bits the processing possibilities are almost endless, at least in theory. In practice many data loggers support only a few basic operations:

Unit conversion. The binary number from the A/D conversion is transformed to a number in engineering units—units that correspond to the physical quantity being measured. This might be a simple multiplication or a more complex transformation such as for thermocouples or thermistors whose voltage/resistance varies non-linearly with temperature.

Signal combination. Sometimes two sensor signals need to be combined to calculate a physical quantity. Examples are, using reference cell current and temperature to calculate irradiance, or using current and voltage to calculate power.

RMS conversion. If a root-mean-square (RMS) value is needed, and not produced on the analog side, then it must be calculated on the digital side.

Data reduction. Commonly not all measurements are stored in the data logs, so an essential processing step is to take sequence of measurements and calculate a smaller number of values for archiving. This is sometimes referred to as decimation. Different decimation rates may be used (ratio of measurements in to values archived), and also different calculations are possible.

Time stamping. Finally, a real-time clock must be consulted to put an appropriate time stamp on each archive value.

E. Measurement Chain Parameters

It should be clear from the foregoing descriptions that a large variety of different measurement chains is possible. In a single monitoring system, there may be several variations to accommodate different signal types, but even for a single signal type, a range of different parameters can be used. In this study we investigate the following parameters:

- the type of analog filter applied before conversion to digital form
- the design or cut-off frequency of the analog filter
- the sampling rate (or interval) of the analog to digital conversion
- the type of data reduction calculation used to determine which values are stored, which is implemented as a digital filter
- the design or cut-off frequency of the digital filter
- the archive rate (or interval) that determines how many values are stored

III. METHOD

The PV system which was measured consisted of sixteen series-connected MS145GG-02 copper indium gallium diselenide (CIGS) modules from MiaSolé. The modules were mounted south-facing with a latitude tilt of 35 degrees from horizontal. The PV array output was inverted to AC power by a Fronius IG Plus 3.0 inverter with a nominal 208 VAC output.

The first step of this study was to acquire the relevant signals at the target rate of 2000 samples per second. This was done by a National Instruments Compact RIO (cRIO) model 9076 with an NI 9239 input module. This fast rate could not be sustained continuously (due to excessive storage requirements), but several complete or nearly complete days with different meteorological conditions were collected. Voltage and current were measured on both DC and AC sides of the inverter, and power was calculated by multiplying them.

The RMS values of the AC voltage and current, and the active power were calculated using a rolling mean window of one AC cycle.

The analysis began with a close examination of the individual signals in both time and frequency domains in order to identify possible challenges for monitoring systems. Subsequently, the operation of hypothetical monitoring system was simulated by sequentially applying digital filters and resampling at lower rates—once to simulate the operation of the acquisition hardware, and once again to represent typical summary calculations, for example calculating an average of several samples over an interval.

The ranges of values or options for each parameter that we investigate are as follows:

- **Analog filter type** is one of:
  - none
  - single-pole low-pass filter
  - two-pole low-pass filter
  - four-pole low-pass filter
  - single pass moving average (60Hz only)
- **Analog filter design frequency**
  - 60 Hz (moving average)
  - 1 Hz (low-pass)
  - 0.1 Hz (low pass)
  - 1 / sampling interval (low-pass)
  - 1 / sampling interval x 2 (low-pass)
- **Sampling interval** ranges from 0.1 to 900 seconds
- **Digital filter type** is one of:
  - none (take the most recent sample)
  - single pass moving average (rectangular window; first-order CIC)
  - dual pass moving average (triangular window; second-order CIC)
- **Digital filter design frequency**
  - 1 / archive interval
  - 1 / archive interval x 2
- **Archive interval** ranges from 1 to 1800 seconds

IV. Filter Properties

The design frequency for the filters is defined as the cut-off frequency for the low-pass filters, and as the location of the first notch, or zero, in the frequency response of the moving average filters. The width of the moving average window is therefore equal to the inverse of the design frequency.

The frequency response of each filter type is shown in Fig. 1. The two types of filters have very different characteristics, the moving average type having very distinct notches at multiples of the design frequency, and the low-pass filters showing no preference for specific frequencies but rolling off in a gradual manner with frequency. A comparison of a moving average filter and a low-pass filter with the same design frequency is not meaningful in general as the design frequency has to be adjusted to achieve specific filtering goals. For example, if a low-pass filter were used to suppress line-frequency noise, its design frequency would have to be much lower.

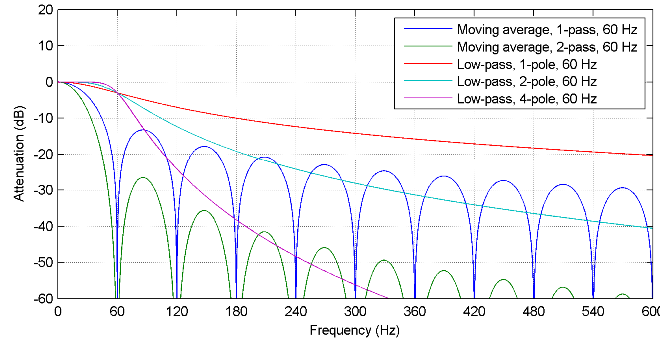

Fig. 1. Frequency response of several filter types

The frequency response characteristics are important when dealing with continuing oscillations in a signal, whether they be sharply defined such as line frequency or broadly distributed in the spectrum such as thermal noise. Changes in irradiance are generally not periodic (discounting the diurnal and annual cycles) but are rather more like randomly occurring step changes with varying slopes, magnitudes and durations, and this drives the characteristics of many of the other signals as well. The spectrum of such a signal can be calculated over different intervals, but it is forever changing.

Another important characteristic of the filters, therefore, is the step response. Fig. 2 shows the positive and negative step response of the same set of filters, with the design frequencies adapted to a realistic time scale. For the moving average filter, additional passes that improve noise suppression also slow the response to rapid step-like changes. The higher-order low-pass filters do not respond quite so sluggishly, but have the possible disadvantage of shooting beyond the actual signal level. With complex signals, therefore, both frequency domain and time domain characteristics of the filters are important.

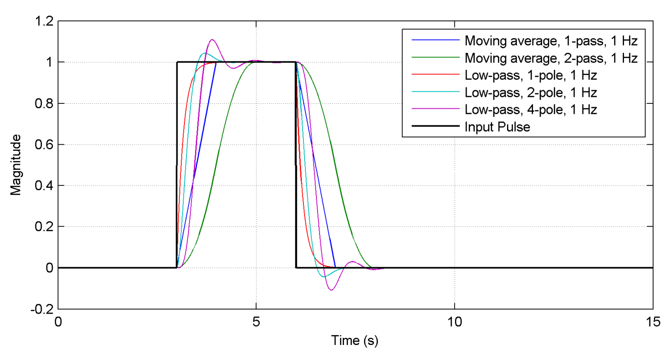

Fig. 2. Step response of several filter types

Many combinations of filter types and resampling rates were then applied to 3-hr data segments (7.2M values!) and evaluated based on how well they were able to produce the true mean values of the signals.

V. RESULTS

A. Signal Analysis

The signal analysis produced a large catalog of results, which is summarized in a table at the end of this section. Several figures are shown here for DC current during a 5-minute interval in the middle of a sunny day. With the external conditions (nearly) constant, the observed signal variations are principally caused by inverter operation.

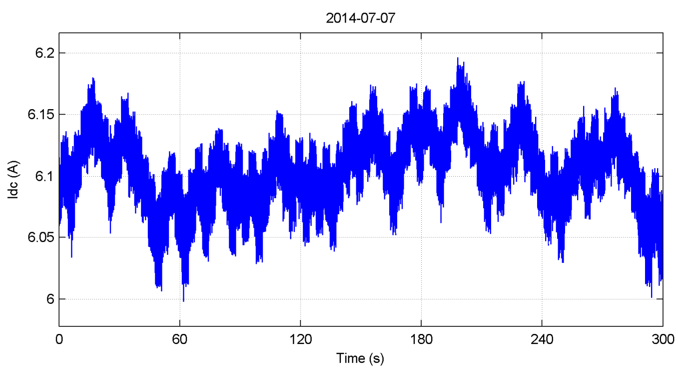

Fig. 3. DC current signal (stable conditions)

Fig. 3 shows the “raw” DC current signal. From this it is immediately obvious that there is considerable fluctuation despite the relatively stable mid-day conditions. The measured values range from 6.0 to 6.2 A, a range of ± 1.6%.

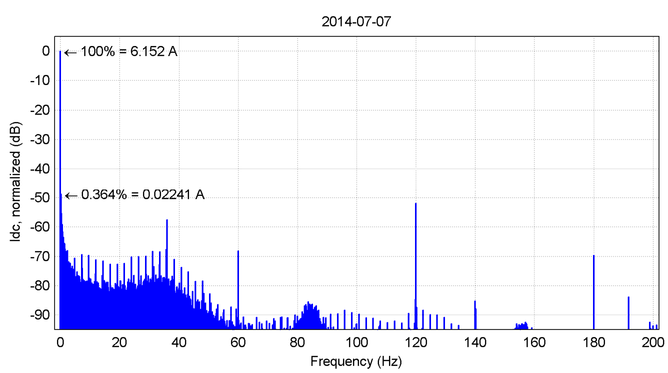

Fig. 4. Average spectrum of DC current signal (stable conditions)

To identify periodic components within this signal, we examine the spectral composition of the signal segment and find quite a number of prominent peaks. (Fig. 4)

The highest peak occurs at 120 Hz, which is the second harmonic of the line frequency and also the frequency at which the instantaneous AC power fluctuates at the output of the single-phase inverter. The large DC bus capacitors inside the inverter are there to decouple the input and output power flow, but there appear to be some residual fluctuations here on the DC side. These are not purely sinusoidal though, since various harmonics of 60 Hz are visible as well.

To visualize the contribution of these 60 Hz harmonics, we remove them from the signal by applying a moving average filter that has a period equal to 1/60th of a second (once forward and once in reverse to avoid time shifts). The resulting filtered signal is shown in Fig. 5.

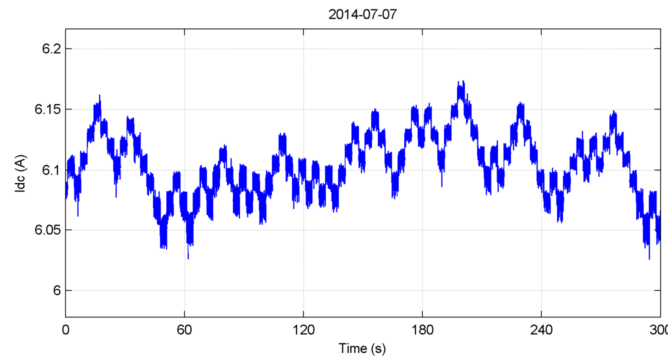

Fig. 5. DC current signal with 60 Hz harmonics removed

This filtered signal appears much more focused than the original, but the largest fluctuations still remain. Looking back at the spectrum we see that the second largest peak occurs at approximately 35.9 Hz, and there is a long series of peaks at 2.4 Hz and multiples thereof. We therefore zoom into the signal to look whether an explanation could be found there.

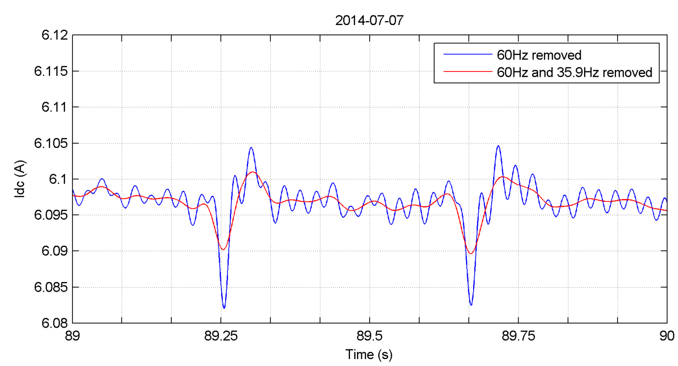

Fig. 6. DC current signal with 60 Hz and 35.9 Hz harmonics removed (close-up)

Fig. 6 shows a one-second segment of the filtered signal and the approximately 36 peaks of the 35.9 Hz signal are readily apparent here. There are also rounded impulse-like perturbations approximately 0.4 seconds apart, which explain the peak at 2.4 Hz (period of 0.416 s) and the associated train of harmonics. But why are they there?

The explanation comes from the fact that the same periodic impulse-like perturbations are seen very strongly on the AC current and AC power. (See [1] for details.) In fact, they occur exactly once every 25 line cycles and are a byproduct of the inverter's active islanding detection system, which probes the grid at regular intervals to ensure that it is still up and connected. (A similar effect was observed every 30 cycles in another system with a different inverter.) The brief perturbation in output current and power destabilizes the DC operating point briefly, and the 35.9 Hz oscillations are probably evidence of under-damped control of the operating point intended to get it back to where it should be as quickly as possible.

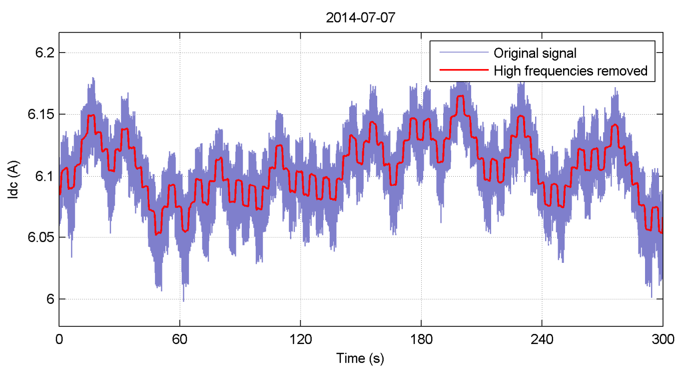

Fig. 7. DC current signal with and without high-frequency content

When this DC current signal is smoothed with a moving average filter of 833 samples (25 line cycles), the step changes of the maximum power point tracking search become clearly visible (Fig. 7).

A similar analysis was carried out on the DC voltage and power as well as their AC counterparts. (See [1] for details.) Observations from this analysis are listed in Table 1.

TABLE 1. SUMMARY OF OBSERVATIONS FROM THE MEASURED SIGNALS

Signal	Amplitude range of high-frequency content	Main high-frequency features
DC current	±1.6%	- line-frequency harmonics - anti-islanding test perturbations (2.4 Hz) - maximum power point tracking step changes (3.3 s)
DC voltage	±1.7%	- line-frequency harmonics - anti-islanding test perturbations (2.4 Hz) - maximum power point tracking step changes (3.3 s)
DC power	±0.1%	- line-frequency harmonics
RMS AC voltage*	±0.2%	- 20/40/60Hz harmonics
RMS AC current*	±11.0%	- anti-islanding test perturbations (2.4 Hz) - higher general noise level than other signals
Mean AC power*	±11.0%	- anti-islanding test perturbations (2.4 Hz) - higher general noise level than other signals

* calculated over one powerline cycle

B. Monitoring Simulations

It is clear from the signal waveforms, that a single sample taken from a segment of the signal can be a significantly different from the mean value for that segment. If the signal deviations from the mean were random noise, one might expect an infrequently sampled signal to be randomly noisy, but as much of the high-frequency content is periodic, infrequent sampling can also can also exhibit much lower frequency aliasing noise. In the signal segment below, for example, the aliasing noise is the result of variations in line frequency and creates a slowly varying offset because the line frequency itself slowly drifts.

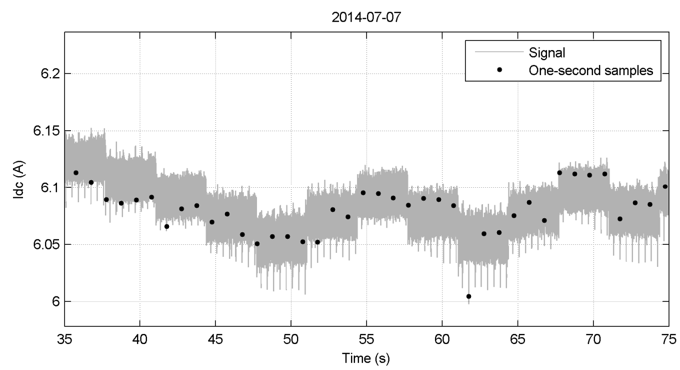

Fig. 8. Slowly varying offset in 1-second measurements of current

Using our high-resolution signals we have simulated the operation of a wide range of hypothetical monitoring systems to see how their accuracy would be influenced by the following factors: analog processing, hardware sampling interval, digital processing, and archiving interval. The following two graphs show how the mean and RMS error of the archived values vary with sampling interval and archive interval.

Note that the general downward trend in error with reduction in sampling interval that is seen in the right half of the graphs does not continue in the left half. The reason for this is the presence of the 2.4 Hz perturbations and their associated harmonics. When these are filtered out prior to sampling, the downward trend becomes consistent over the whole range of sampling intervals.

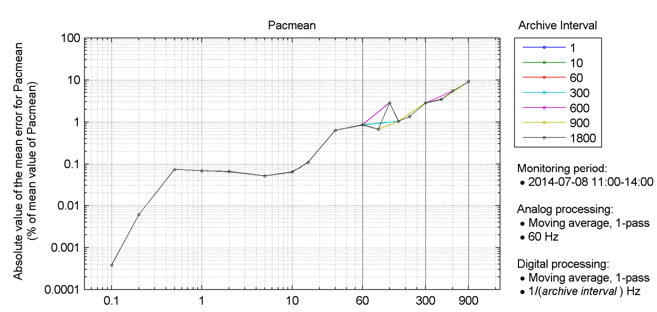

Fig. 9. Mean error of archived AC power values for a 3-hr period

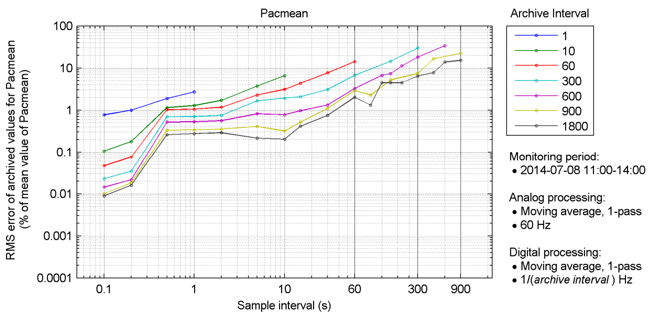

Fig. 10. RMS error of archived AC power values for a 3-hr period

This 2.4 Hz filter, just like the more commonly found 50/60 Hz line frequency filters, is optimized for a specific type of unwanted signal content. When we know what the sampling interval is going to be, it is also possible to choose an optimal filter on that basis instead. Such a filter is not hard to define: it is a classical anti-aliasing filter and should filter out frequencies higher than half of the sampling frequency. Indeed, when we introduce a fairly simple 2-pole low-pass filter with the cut-off frequency adjusted for each case, both the mean and RMS errors drop by roughly one order of magnitude, as we show in [1].

VI. Conclusions

In this study we have investigated how the interplay between complex signals and the way in which they are measured can lead to errors in the data delivered by PV monitoring systems.

The signal characteristics we report were observed over relatively short time intervals on a single PV system, which means that they certainly cannot be considered as representative of all systems. But the fact that they were all found on the first system we examined, suggests that signals in other systems are likely also affected, although maybe not for the same reasons and not in the same proportions. Further evidence needs to be gathered from other operating PV systems before more general statements can be made.

To explore how measurement errors can arise in PV monitoring systems, we simulated their operation using a wide range of sampling intervals and archive intervals, and using several different filtering options. We saw how the anti-islanding system perturbations dominated the measurement errors in AC power over a specific range of sampling rates, and found that a simple two-pole low-pass filter preceding the analog-to-digital conversion could be tuned to this signal content to reduce those measurement errors. Furthermore, we showed that the low-pass filter could be tuned to reduce the measurement error at any sampling rate. As PV monitoring systems often have sampling rates that are too low to capture rapid fluctuations in irradiance and power, the addition of a low-pass filter presents itself as a possible solution to obtaining more accurate average values for many signals.

Because there is a strong link between various parameters of a monitoring system and the quality of the archived values, it is very important to know what those parameters are. Documentation for PV monitoring systems should always include specifications of filtering methods, sampling rates, summary calculations, archive rates and time stamp conventions, and this metadata should always accompany the data files that are produced. And if these parameters are to be optimized, then it would also be helpful to obtain more information from the inverter manufacturers about possible inverter-induced perturbations.

The present study focused on individual signals and the accuracy of the archive values that were produced. Future work should explore the accuracy of the relationships *between* signals, which are the key to understanding and assessing system performance. The true relationships between signals can be distorted by excessively long averaging periods, by taking sequential measurements rather than simultaneous ones, or by unequal response rates somewhere in the measurement system. We expect that a better understanding of all these effects will lead us to more accurate PV system performance assessments.

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